

X-raying Active Galaxies with the New Generation of X-ray Observatories: Ionized Outflows and High-Redshift Studies

W.N. Brandt, S.C. Gallagher, & S. Kaspi

Department of Astronomy & Astrophysics, 525 Davey Laboratory, The Pennsylvania State University, University Park, Pennsylvania 16802

Abstract. We briefly review X-ray studies of ionized AGN outflows and high-redshift AGN. We discuss recent progress with *Chandra* and *XMM-Newton* as well as prospects and requirements for future X-ray missions.

1. Introduction

The main goals of X-ray studies of active galactic nuclei (AGN) are (1) to measure the key parameters of the accreting black hole system, such as the black hole mass, spin, and accretion rate, (2) to determine the distribution, dynamics and physical conditions of nuclear and circumnuclear material (e.g., the accretion disk and its corona, the torus, jets, winds, clouds, and any circumnuclear starburst), and (3) to understand the cosmic X-ray evolution of AGN. The talks and posters at this symposium have made it clear that studies with *Chandra* and *XMM-Newton* have already touched all aspects of AGN research, and it is wonderful to see such progress.

This proceedings paper will briefly cover two important areas of AGN research that should show exciting growth during the new century: (1) X-ray studies of ionized outflows in Seyfert galaxies and quasars, and (2) X-ray studies of the highest-redshift AGN. Only limited citations will be possible due to space limitations; our apologies in advance.

2. Ionized Outflows in Seyfert Galaxies and Quasars

One of the most revolutionary aspects of the new observatories are the gratings spectra they regularly provide; in AGN outflow research these have given qualitatively new information by increasing the number of spectral features available for study from 2–3 to 30–60 (see Figures 1 and 2). These features include absorption lines, emission lines, unresolved transition arrays, and edges. They provide constraints on the dynamics, geometry, and physical conditions in an AGN outflow. For example, the Doppler shifts of absorption lines have shown that the X-ray absorber is indeed outflowing with typical bulk velocities of a few hundred km s^{-1} and can have a velocity dispersion comparable to the bulk velocity (e.g., Kaspi et al. 2001 and references therein). In some cases multiple velocity components and P Cygni profiles are discernible. In terms of geometry, X-ray emission-line strengths confirm that these outflows have large covering factors

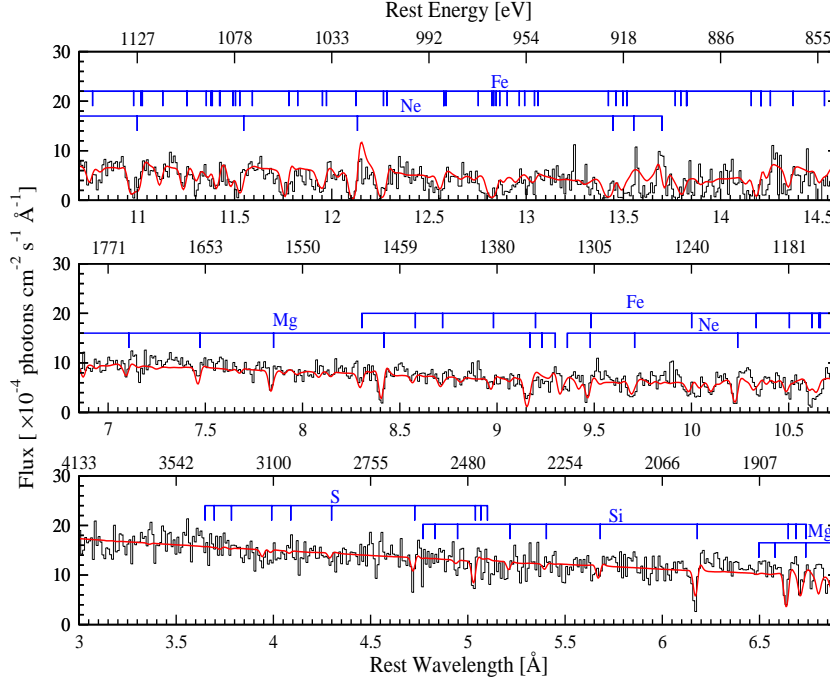


Figure 1. Part of the Cycle 1 *Chandra* HETGS spectrum of the bright Seyfert 1 galaxy NGC 3783. The histogram shows the data, and the smooth curve shows a photoionization model for the data. The H-like and He-like lines of Ne, Mg, Si, and S as well as the strongest lines contributing to the model are marked. From Kaspi et al. (2001).

(≈ 0.3 – 0.8), but the characteristic distance from the black hole and radial extent are still poorly constrained. Pinning down these quantities will require a better understanding of the physical conditions in the absorbing gas, particularly its density. It is also crucial to determine if the gas is in photoionization equilibrium and to assess its abundances and dust content. Hopefully the long gratings observations currently being performed will provide the requisite constraints.

Aside from the measurement of key parameters, X-ray gratings studies have also allowed a re-evaluation of the basic interpretation of the low-energy spectral complexity seen from many Seyfert galaxies (e.g., Branduardi-Raymont et al. 2001; Lee et al. 2001); some have argued for the presence of accretion-disk lines formed close to a Kerr black hole. The current debate over these lines should be resolvable with better spectral data and constraints on the rapid variability of the low-energy spectral complexity.

Looking further into the future of X-ray outflow studies, it is important that X-ray grating spectrometers achieve better spectral resolution (also see the paper by M. Elvis in these proceedings). The current ones, while a *major* advance, have velocity resolutions comparable to that of *IUE* (≈ 300 – 600 km s $^{-1}$). Just as *HST* revealed unresolved structure (e.g., multiple velocity components) in many of the ultraviolet lines studied by *IUE*, future X-ray missions may further subdivide the currently detected X-ray absorption lines (see Figure 3). Larger

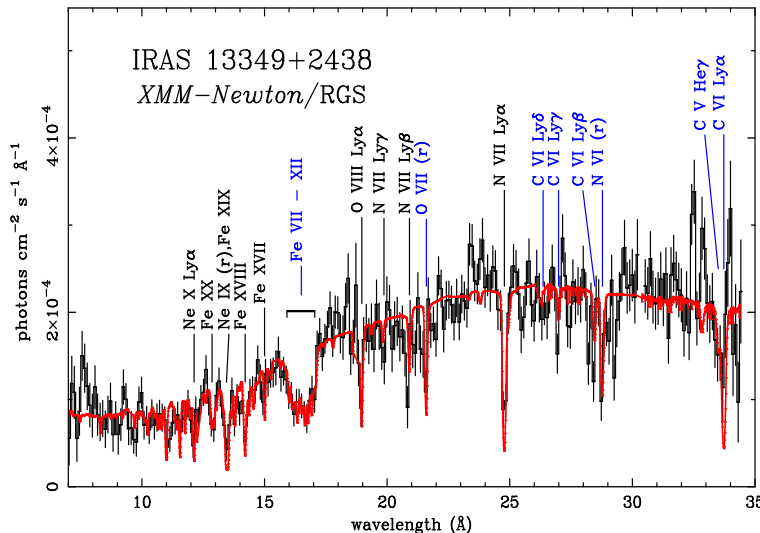


Figure 2. The AO1 *XMM-Newton* RGS spectrum of the infrared-loud quasar IRAS 13349+2438. The histogram shows the data, and the smooth curve shows a model for the data. The strongest observed lines are marked; note the unresolved transition array from ≈ 16 – 17 Å that explains some of the previously detected spectral complexity. From Sako et al. (2001).

collecting area is also of great importance; currently even the brightest Seyfert galaxies require gratings observations of $\gtrsim 1$ day, and X-ray gratings studies of the more powerful outflows known in luminous quasars [e.g., Broad Absorption Line (BAL) quasars] are essentially impossible. The few X-ray CCD spectra available for BAL quasars suggest that X-ray BALs may be awaiting discovery (e.g., Gallagher et al. 2001; Mathur et al. 2001). Given the large X-ray column densities observed in BAL quasars, constraints on the velocity structure of the X-ray absorbing gas will have fundamental implications for our understanding of the energy budget of luminous AGN.

3. X-rays from the Dawn of the Modern Universe

One of the main themes in astronomy over the coming decades will be the exploration of the dawn of the modern Universe, when the first stars, galaxies, and black holes formed, ending the cosmic “dark age” (e.g., the USA National Research Council 2000 Decadal Report). X-ray astronomy can play a crucial role in this project by allowing studies of warm and hot objects in the early Universe, thereby complementing studies of the cooler Universe with observatories such as *NGST*, *ALMA*, *Herschel*, *SIRTF*, and *SKA*. Large X-ray missions such as *XEUS* (\approx \$2 billion) are being planned to focus on the first massive black holes (at $z \approx 5$ – 20) and black hole evolution.

It is critical to use *Chandra* and *XMM-Newton* to lay the observational groundwork for future high-redshift X-ray efforts. At present, our knowledge

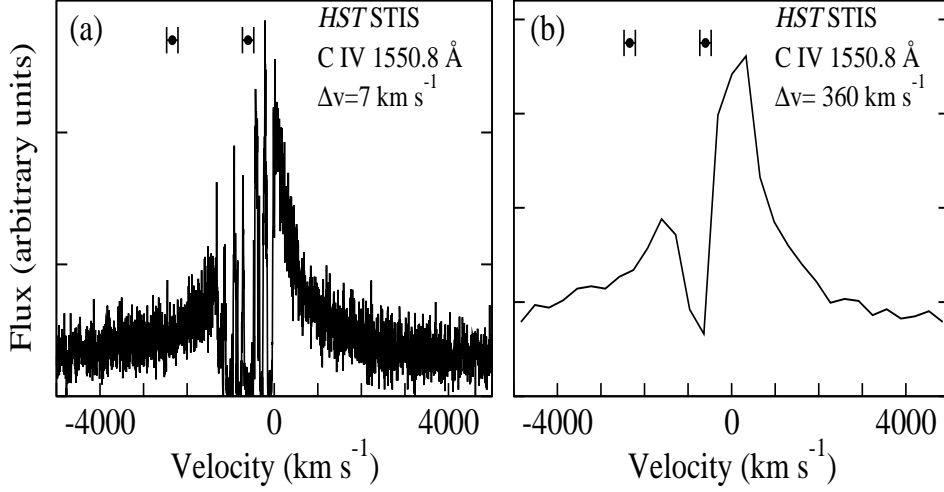


Figure 3. *HST* STIS velocity spectra of the C IV 1548.2 Å and 1550.8 Å emission and absorption lines seen from the bright Narrow-Line Seyfert 1 galaxy NGC 4051. Panel (a) shows the lines at full resolution; the “scruffy” structure from ≈ -1000 km s $^{-1}$ to ≈ 0 km s $^{-1}$ is due to the presence of at least nine kinematically distinct absorption components. When the full-resolution spectrum is smoothed to the approximate velocity resolution of the *Chandra* HETGS in panel (b), the kinematic components are not visible and the resulting absorption “line” resembles the lines seen in X-rays by the *Chandra* HETGS. The X-ray absorbers seen in Seyfert galaxies may be subdivided into further systems that cannot be resolved with current X-ray instruments. The two dots with error bars near the tops of the panels show the velocities of the X-ray absorption components that *can* be resolved by *Chandra*; note that only one of the two X-ray absorption components shows corresponding ultraviolet absorption. From Collinge et al. (2001).

about the $z > 4$ X-ray Universe is unfortunately quite limited. Only 16 objects at $z > 4$ have published X-ray detections: 10 quasars, four blazars, one Seyfert galaxy, and one gamma-ray burst afterglow. The quasars and Seyfert galaxy have limited counts (typically 10–50); their broad-band spectral energy distributions look roughly consistent with those of lower-redshift objects (e.g., Kaspi, Brandt, & Schneider 2000; Brandt et al. 2001a). The four blazars are the only $z > 4$ objects with X-ray spectra. Three of them show low-energy cutoffs apparently due to X-ray absorption (e.g., Fabian et al. 2001 and references therein), extending the absorption-redshift trend found for radio-loud quasars at lower redshifts (e.g., Fiore et al. 1998).

Figure 4 shows the redshift distribution of published luminous AGN at $z > 4$ with published X-ray detections marked. Most of the X-ray detections are at $z < 4.6$, and there is only one at $z > 5$ separated from the others by $\Delta z > 1$. This object, SDSS 1044–0125 at $z = 5.80$, was recently detected by *XMM-Newton* and was found to be ≈ 10 times weaker in X-rays than expected given its optical flux (Brandt et al. 2001b). Absorption was proposed as the

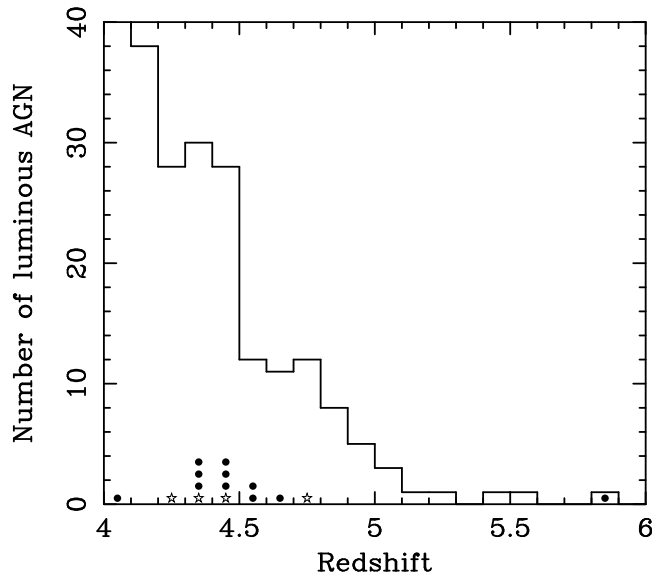


Figure 4. Histogram of the redshift distribution of published luminous AGN at $z > 4$. The stars denote blazars detected in X-rays, and the solid dots denote quasars and a Seyfert galaxy detected in X-rays.

most likely cause of its X-ray weakness, and BALs have indeed recently been discovered by Maiolino et al. (2001) and F.H. Chaffee et al., in preparation. Given that SDSS 1044–0125 is likely to be an unusual member of the $z > 5$ population, at present we have *no* constraints on the X-ray properties of normal $z > 5$ quasars. X-ray astronomers are largely “groping in the dark (age)” when attempting to plan missions to study AGN at $z \approx 5$ –20. Fortunately, over the next five years surveys such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) should provide a large number of $z = 5$ –6.5 AGN, many of which should be bright enough for study in X-rays. It should also be possible to detect moderate-luminosity AGN at $z = 5$ –10 in the deepest X-ray surveys (e.g., Haiman & Loeb 1999); follow-up of such objects will prove challenging. Moderate-to-extreme photon starvation will limit our ability to perform X-ray spectroscopy of the highest-redshift AGN for the next few years, even with *XMM-Newton* (barring fortuitous finds such as lensed quasars or bright blazars). However, prospects are good for *Constellation-X* and *XEUS* which should be able to deliver many 10,000–100,000 count spectra of the highest redshift AGN (see Figure 5).

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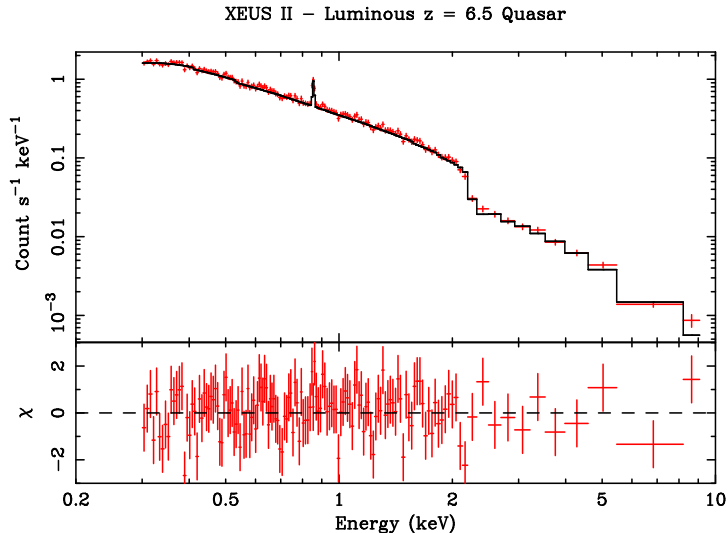


Figure 5. Simulated 40 ks *XEUS* (final configuration) spectrum of a luminous $z = 6.5$ quasar such as might be found by the SDSS. The quasar has a power-law spectrum with a photon index of $\Gamma = 2$, a Galactic column density of $N_{\text{H}} = 2 \times 10^{20} \text{ cm}^{-2}$, and an observed-frame 0.5–2.0 keV flux of $4 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$. A narrow iron $\text{K}\alpha$ line at 6.4 keV is included with a rest-frame equivalent width of 150 eV.

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